The Galileo Mission

From orbit around Jupiter, the Galileo *spacecraft will take the closest look ever at the planet and its natural satellites*

by Torrence V. Johnson

On December 7, 1995, a new form of shooting star will blaze briefly in Jupiter's sky, It will be not a meteor or comet but a device manufactured on the earth that will slam into the thin gases Of the upper Jovian atmosphere at nearly SO kilometers per second. Within minutes a parachute will unfurl 10 slow the projectile, and the remains of its heat shield will fall away, For a little more than an hour, the exposed instrument will descend, sending data on composition, temperature, pressure and cloud structure to its parent craft, *Galileo,* passing 200,000 kilometers overhead.

Galileo will store the signals for transmission to scientists waiting Oh the earth. As the probe's signals fade away, a rocket on *Galileo* will fire for almost an hour, placing the craft in a large, looping orbit around the planet. After visiting two other planets and two asteroids on its six-year Journey—and cm the way making some unexpected discoveries—the spacecraft will finally be at its intended destination: Jupiter. Three hundred and eighty-five years after Galileo Galilei discovered the Jovian moons, a man-made satellite bearing his name will join their endless circuit.

Project Galileo was born in the mid-1970s, after *Pioneer 10* and *Pioneer 1 J* had flown by Jupiter and the ambitious Voyager missions to the ends of the solar system had been initiated. It was clear (bat Jupiter and ita peculiar moons—forming a type of miniature solar system—were worth more than a passing glance. In 1976 a team led by James Van Allen of the University of Iowa presented to the National Aeronautics and Space Administration a dual mission plan: an entry probe to study Jupiter's atmosphere as well as a sophisticated device that would circle the planet about 12 times over two years, transmitting information about Jupiter, its moons and Its mammoth magnetic field [W *box on pages 48 and* 49].

The mission was approved by Congress, and *Galileo* was slated to become, in January 1982, the first planetary spacecraft launched by shuttle, But the shuttle program rim into technical hitches, as did the three-stage solid-fuel rocket needed to send *Galileo* all the way to Jupiter. After several other schemes had been considered and discarded, the propulsion system was replaced by one using a single, powerful rocket fueled by liquid hydrogen, and the launch was reset for May 1986.

Then, in January 1986, soon after *Galileo* was trucked from the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., to the Kennedy Space Center in Cape Canaveral, Fla., the tragic *Challenger* accident occurred, killing seven people on board. All subsequent shuttle launches were put on hold for an indefinite period. Moreover, *Galileo's* liquid-hydrogen rocket was deemed too dangerous to transport in a shuttle's cargo bay and was dropped from consideration. The only propulsion system that *Galileo* was now allowed, a two-stage solid-fuel rocket, would not be energetic enough to get it to Jupiter.

Fortunately, a mission design team at JPL came up with an innova-

[redacted]

GALILEO will approach Io, Jupiter's volcanic moon, on December 7, 1995. The combined action of *Galileo's* thrusters and Io's gravitational pull will place the spacecraft in orbit around Jupiter. Because of a malfunctioning tape recorder, however, *Galileo* may not be able to make observations during this closest encounter.

tive solution. *Galileo* could swing by Venus and the earth, gathering energy from the planets' motions around the sun to supplement its inadequate rocket. It would, in the end, be able to reach Jupiter—and on the way provide even more scientific observations than had been planned.

The Inner Solar System

and its solid-fuel rocket

Galileo went into space on October 18, 1989, riding in the cargo bay of *Atlantis*. After deployment from the shuttle, ~~some of Galileo's~~ solid-fuel rockets fired, making the spacecraft fall, paradoxically, toward the center of the solar system. The new VEEGA trajectory (for Venus Earth Earth gravity assist) would take the spacecraft to Venus and twice past the earth before it finally left for Jupiter. Apart from the planetary encounters, the devious route included two passages through the asteroid belt. They involved close encounters with two asteroids, members of the solar family that had never been seen at close range.

On the way to Venus and, indeed, all through its long cruise, some of *Galileo's* instruments were kept busy scrutinizing interplanetary space. The magnetometer monitored the interplanetary magnetic field and the solar wind, made of charged particles flowing from the sun over enormous distances. The extreme ultraviolet instrument also proved immediately useful. *Galileo's* measurements were used to calculate how radiation from the sun varies with the latitude from which it is emitted, allowing researchers to update models of the sun's dynamics.

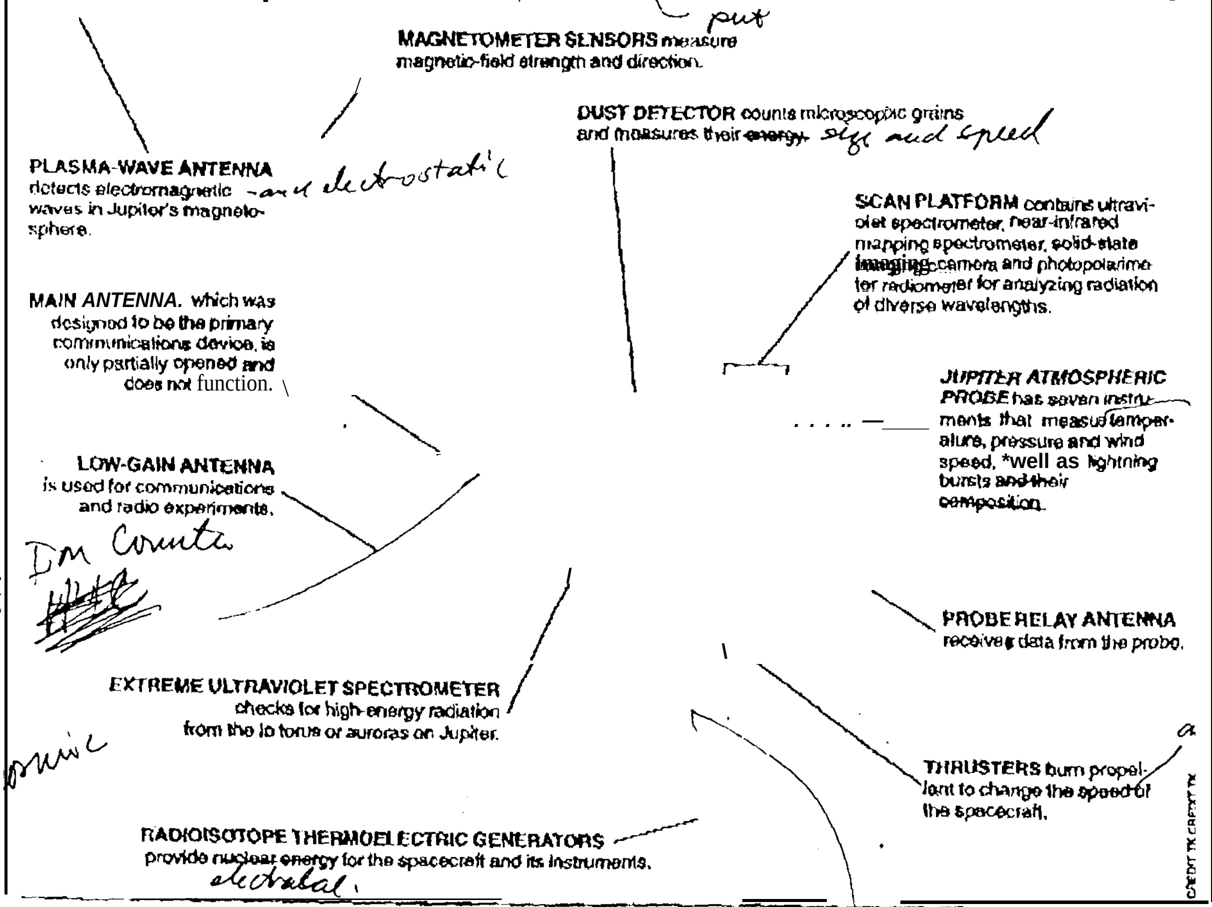
The radio transmitters, which are used for communication, also turned in valuable science. From the opposite side of the sun, *Galileo* sent radio waves to JPL that just grazed the visible solar surface. Turbulent processes on the sun and the ways in which material spurts off into the solar wind were measured via their effects on the radio waves pass-

Jupiter's Instrumented Satellite

Galileo is unusual in having two segments, one of which spins; the other is stationary. Rotation imparts stability and also allows the communications antenna, which lies along the spin axis, to point steadily to the earth. Survey instruments that scan the entire sky are mounted on the main, rotating section; devices that have to be directed toward a particular object for a long time are on the stationary 'scan platform. The Galileo mission involves significant cooperation with the Federal Republic of Germany, which supplied the propulsion system and several of the instruments.

The probe will enter Jupiter's atmosphere just as *Galileo* arrives at the planet on December 7. That same day, Io's gravity, ~~combined with~~ rocket thrusters, will ~~pull~~ put *Galileo* into orbit around Jupiter. From that position it will transmit data for two years. —T.V.J.

aided by Io's gravity



Plasma detector — measures low energy charged particles trapped in Jupiter's magnetic field

Energetic Particles Detector measures high energy ... Allen belt ... particles ing through.

Galileo had to fly the first leg of its mission with its main, umbrellalike antenna furled and hidden behind a sunshade that protected it from the direct rays of the sun. The configuration made this important device, designed to transmit data at high rates, unusable. The spacecraft also has a small antenna at either end, but these were too weak to send much information over long distances.

As a result, *Galileo*'s tape recorder was programmed to store information about Venus during the few hours of closest approach. The bits were relayed to the earth over one of the two low-gain antennae—the one pointing to the earth- . when *Galileo* returned for its first visit in December 1990. The proximity ensured that the signals were received loud and clear despite the low power at which they were transmitted. Infrared images taken by *Galileo* penetrated deep within the atmosphere of Venus and gave the closest view ever of the structure and dynamics of its lower cloud layers.

Galileo was also able to observe the earth from the perspective of an interplanetary explorer, producing a stunning movie of our watery planet. The spacecraft examined the outer expanses of the earth's magnetic field and took the first measurements of the moon's far sick since the day. of the Apollo program. These images revealed ancient volcanic processes in regions not visited by astronauts and beautifully confirmed the existence of an ancient, huge impact basin on the far side, the South Pole–Aitken basin.

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WINDING ROUTE to Jupiter has taken *Galileo* past Venus, past the earth twice and through the asteroid belt twice. Once in orbit around Jupiter, *Galileo* will have 11 close encounters with the planet's four largest moons.

A Communications Disaster

Soon after swinging past the earth for the last time, *Galileo* encountered a major technical problem. Now that the spacecraft was far enough from the sun, ground controllers commanded its large antenna to unfurl. The motors ran for less than 10 seconds and stalled. Later analysis showed that several, probably three, of the antenna's ribs were not deployed, leaving the instrument a useless, twisted sack of metal mesh

Intense efforts over several years have failed 10 open the antenna. The best engineering judgment is that the ribs arc permanently jammed, probably because of the loss of lubricant during the long truck rides the spacecraft took from the Pacific coast 10 the Atlantic in 1986, back to the Pacific when launch was delayed and again to the Atlantic in 1989.

For a few devastating months, the team thought it had lost much, if not all, of the orbital mission. The probe's data could be returned to the earth with the small antenna that had served since launch for communications. But plans for gathering data during orbit depended heavily on the undeployed antenna, designed to transmit at 134,000 bits per second. A series of brainstorming sessions slowly convinced the planning team that a good deal of the science could still be done with the small antenna. ~~despite its transmission rate of only 10 bits per second from the distance of Jupiter.~~

Of immediate concern was the upcoming rendezvous with Gaspra, the first meeting of a spacecraft with an asteroid. Plans for the Gaspra observations were already far along, relying on fast communications through the main antenna, both for maneuvering *Galileo* close to the asteroid and for sending back information.

Waling feverishly, engineers figured out how to replace the planned 20 or more pictures needed for navigation with only five. (The camera shutter was left open so that the stars appeared as streaks; one picture therefore served for several.) There was just enough time to receive these critical images, which helped to fix the exact position of *Galileo*, from the low-gain antenna. The international astronomical community pitched in with a campaign of observations of Gaspra's orbit, a vital element in determining where the spacecraft would be with respect to the asteroid.

The gigabit magnetic tape recorder on *Galileo* that had served for the Venus flyby was recruited for storing the Gaspra images. Because *Galileo* was to visit the earth one more time, the recording could be played back over the low-gain antenna while the spacecraft was nearby. This strategy made it possi-

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VENUS was imaged in infrared light by *Galileo* during its flyby. The radiation ~~penetrated~~ deep within the atmosphere, allowing the inner layer of clouds to be seen for the first time.

ble to retain the most important experiments despite the loss of immediate transmissions from the main antenna.

Meeting Gaspra and Ida

Nevertheless, we reclaimed a few images immediately after the encounter to see what our efforts had netted. The navigation had been extraordinarily precise. The pictures offered the first close-up look at an asteroid, revealing an irregularly shaped rock with many small impact craters but fewer large craters than expected. Many of the particles in the asteroid belt were apparently smaller than had been estimated. And it seemed that Gaspra must have fragmented quite recently, about 300 to 500 million years ago, from a larger body made of rock.

The remaining data were resumed when *Galileo* came home for the last time, in December 1992. It showed, in-

why Jupiter?

The *Voyager 1* flybys of 1979 convinced astronomers that Jupiter and its moons are far more interesting than they could have imagined. With its planet-size moons in circular, coplanar orbits, the Jovian system looks remarkably like a small solar system.

Jupiter itself is in many ways like a star. It contains 70 percent of the mass of all the planets in our solar system combined and is composed mainly of hydrogen and helium. Gravitational energy released when the planet formed 4.5 billion years ago is still trapped deep inside and seeps out slowly, so that the planet radiates almost twice the amount of energy it receives from the sun.

In addition, Jupiter's atmosphere most likely represents the best sample of the original nebula from which the solar system formed. The nebula contained mainly light elements, especially hydrogen and helium, which rocky planets such as the earth either never had or lost a long time ago. In the sun itself, the gases have been modified by thermonuclear burning. But on the giant planet everything has been preserved, held by the massive gravity. *Galileo's* probe will reveal the composition of this gas and dust, refining our understanding of how the solar system came to be.

Jupiter has no surface in the usual sense. The hydrogen becomes denser with depth, condensing into a hot liquid at rather shallow levels. Into this hydrogen ocean falls a perpetual rain of helium. further down, hydrogen becomes a metal, very likely providing the high electrical conductivity required for generating Jupiter's powerful magnetic field.

Through behaves as a

Jupiter is also a massive natural laboratory. A global atmospheric model should be applicable not only to the earth but also to other planets; Jupiter, with its high gravity, fast spin and unusual chemistry, provides a testing ground as different as possible from the earth. Many of the entry probe's measurements are designed to provide "ground truth" for calibrating atmospheric models, which will ultimately help in understanding the earth.

Jovian Satellites

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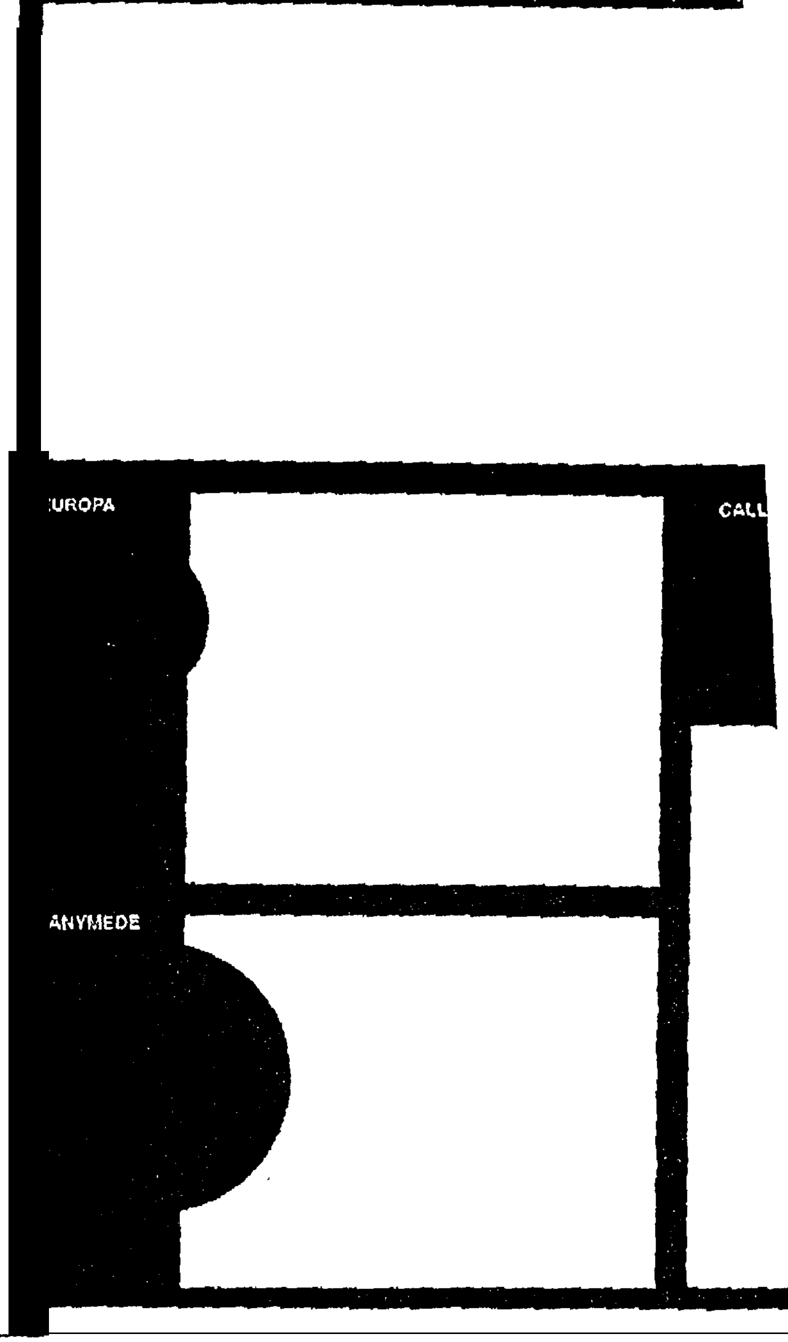
Jupiter's ~~14 satellites are believed to have formed out of a cloud of gas, dust and ice centered around the planet,~~ much as the planets formed around the sun. The large rocky moons, Io and Europa, are closest to Jupiter—

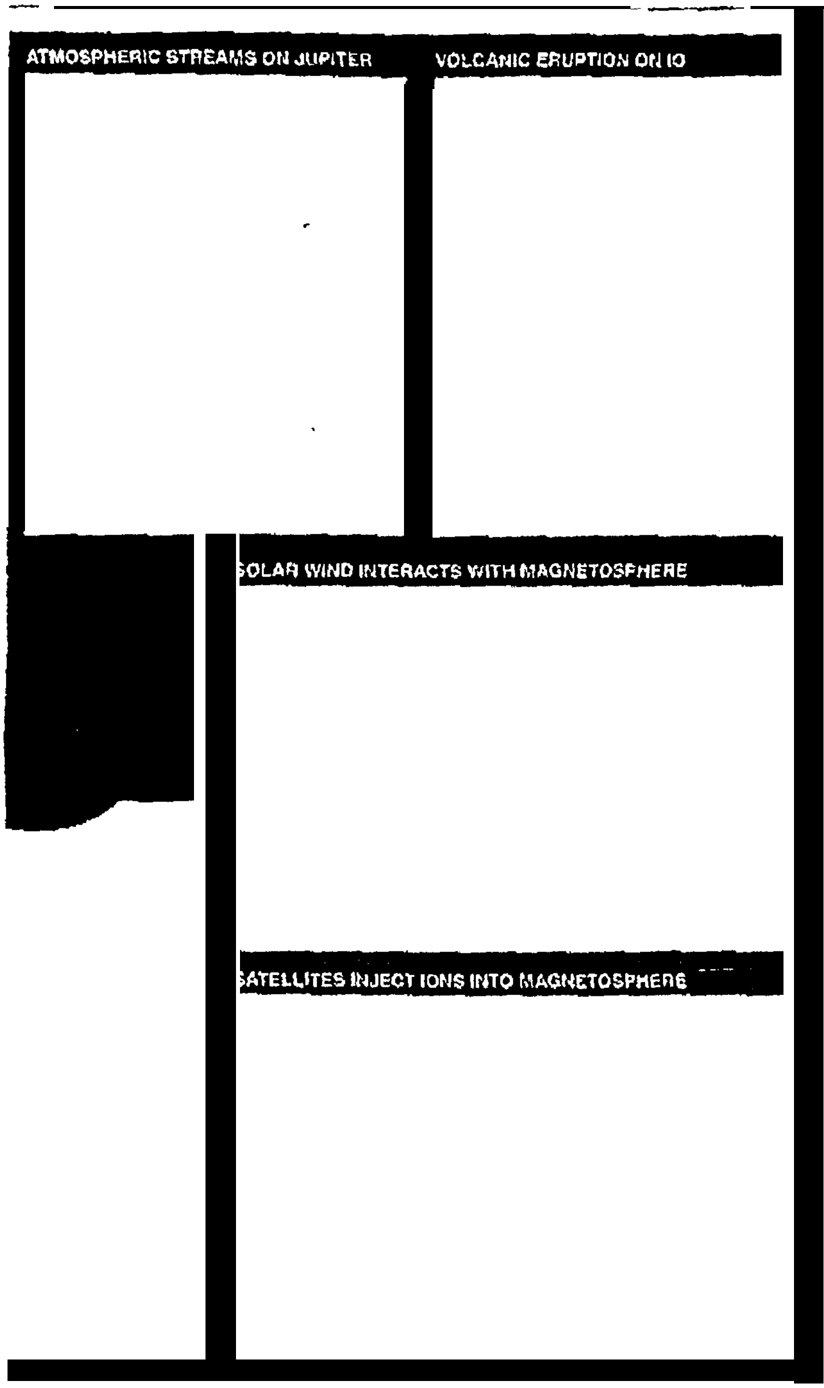
JUPITER WITH ITWO GALILEAN SATELLITES, IO (LEFT) AND EUROPA (RIGHT)



...changed direction close to Gaspra, as though encountering a *magnetic* obstacle. If Gaspra has a ~~strong~~ magnetic field, it could have affected the solar wind field in a similar way. Evidently, the magnetic properties of asteroids were far more interesting

The second encounter with the earth was an opportunity to conduct vital calibrations. It afso provided excellent views of the poorly studied north polar regions of the moon and, as a final "bon voyage" gift, a beautiful movie of the moon and the earth together.

The gravitational boost from the earth sent the craft toward its final destination on December 8, 1992. (Incidentally, it also slowed the earth down by a minuscule fraction; luckily, this amount is tiny compared with the gravitational jostling from other planetary bodies, and we were not required to file a new



just as terrestrial planets such as Mercury and Mars are the innermost ones in the solar system. Further out, Ganymede and Callisto have far more of the lighter elements, such as hydrogen (in the form of ice).

Each of these large satellites is also a fascinating body in its owrt right, worthy of a visit if it were instead orbiting the sun as a small planet Io, about the size of the earth's moon, is the most volcanically active body in the solar system, being completely resurfaced by lava every 100 years. Unlike the earth, whose volcanoes are energized by heat from radioisotopes, Io's are heated by tidal distortions created by Jupiter and its other moons. The volcanic clouds create a patchy atmosphere of sulfur dioxide, part of which escapes from the planet; the remainder freezes out onto the surface. few

Europa, also the size of the earth's moon, has a strange cracked, icy surface that makes it 10 time s-a bright in reflected light. Ganymede and Callisto are heavily *cratered,* aged moons, both about as large as Mercury, containing large amounts of ice. *Galileo's* 11 close encounters with these four largest satellites will reveal countless details, such as the composition of Io's lava and Callisto's rocks ~~and~~ the thickness of Europa's Icy crust. and it ~~...~~ an

A Strong Magnetism

The area around a planet that is dominated by its magnetic field is called the magnetosphere. Jupiter has the most extensive magnetosphere in the solar system: if the volume of space it encloses could somehow be made visible to the human eye, it would look larger than the full moon in our night sky.

The magnetosphere forms a barrier to the electrically charged particles in the solar wind, forcing it to detour around the invisible block. A shock wave forms at the upstream, or sunward, edge of the magnetosphere; downstream, the magnetic field is elongated to form a "magnetotail." The magnetosphere is home to highly energetic charged particles, immense currents and a bewildering array of electromagnetic waves.

A huge spinning ring, or torus, of sulfur and oxygen ions surrounds Jupiter and makes up the inner part of the magnetosphere. The material is stripped off from Io, which must supply about a ton of it per second. *Galileo* will study regions and processes in the Io torus and the magnetosphere that were inaccessible to previous spacecraft. —*T.V.J.*

speck

glitch means a mistake to electrical signals

JAILBARS, slices of images taken of the asteroid Ida, were returned to the earth so that the interesting parts could be located without the entire image having to be sent. (The failure of the main antenna necessitated such extreme economy in the transmission of data.) The jailbars revealed a small speck alongside Ida (*left*); the full image (*right*), when reclaimed, revealed the ~~glitch~~ to be a rock about a kilometer wide, orbiting Ma—the first known asteroidal moon.

x

environmental impact statement]) The trajectory was adjusted so that *Galileo* would arrive at Jupiter on December 7, 199S. On the way, it would also encounter asteroid Ida, on August 28, 1993.

The Ida meeting presented new challenges. There was no prospect of using the stuck main antenna, and no mom passages by the earth to sidestep the communications bottleneck. The transmission rate for sending Ida's data would never exceed 40 bits per second. Yet the scientists wanted to make observations twice as close to Ida as to Gaspra. Because Ida is about twice the size of Gaspra, my portrait would also have four times the surface area,

An intense navigational effort was set into motion to get even better data for Ida than for Gaspra. Techniques were developed to search the recorded tape so that the empty "black sky" frames need not b-e returned. leaving the antenna free to transmit only the essential images. Nature helped somewhat: Ida has a period of 4.65 hours, about two thirds that *Of* Gaspra, so that *Galileo* would see all *the* sides of Ida from closer range.

The initial images showed Ida to be an extremely irregular object about 56 kilometers long, with a very heavily cratered surface. Ida is a member of an asteroid group called the Koronis family, believed to be left over from the breakup of a larger parent body about 100 kilometers across. Some theorists *had argued* that the breakup occurred no more than tens of millions of years ago. Ida's crater-scarred, apparently ancient surface suggests instead that the Koronis family and perhaps others as well may be one or more billion years old.

Ida's Son

There was another Sm'prise in store. In February 1994 scientists began to screen the remainder of the Ida tape. Small parts of some of the image frames had been obtained as "jailbars"—sequences to which a few scanned lines were sent, many were skipped. then a few more were returned, and so on to the end of the frame. The regions containing Ida were Jointed so that they could be played back in full later.

Examining the jailbars for the first time, imaging team associate Ann Harch noticed an odd speck alongside Ida. Ruling out a UFO as somewhat unlikely, the team checked *for* astronomical Sources that might inadvertently *have* appeared in the background. Finding none, they concluded that they had found amid asteroid, ~~possibly~~ Probably a moon, next to Ida.

The Infrared team, which afso had jailbars, confirmed the asteroid's *presence*. The imaging and infrared groups quickly realized they had slightly different views of the same object. A rapid calculation of parallax angles showed that the rock was about 100 kilometers from the center of Ida and had not moved much in the fow minutes separating the observations. The small body. close to a larger asteroid and moving very slowly, was almost certainly a satellite. The International Astronomical Union named it Dactyl, after the Dactylos, the sons of Ida and Jupiter.

It happened that essentially every view taken of Ma also contained Dactyl. The high-resolution images revealed the moon to be a potato-shaped, pockmarked object, clearly not some recent collisional fragment. It was in M orbit with a period of 24 hours or more. The range of possible Orbits that fit ~~this deduction~~ can help constrain the mass and therefore the density of Ida, which turns out to be similar to that Of many rocks and stony meteorites.

The discovery of Ida's moon raised marry questions. what, for instance, was its origin? A collision could have sent a piece Of debris from Ida itself into orbit. (A variant of this idea is that the earth's room formed when a "megaimpact" blasted material *off the* earth, which then coagulated *With* debris from the impactor [see "The Scientific Legacy of Apollo," by G. Jeffrey Taylor; SCIENTIFIC AMERICAN, July 1994]), But then the fragment would have Jrad to collide with some other strategically placed debris, Or else it would simply have fallen back to Ida. More likely, both Dactyl and Ida were produced when the parent bOdy 0! the Koronis family broke up. If the two fragments stayed relatively close to each other, they could have become gravitationally bound.

Scientists are divided about how likely an asteroid is to acquire a satellite and how long the latter can survive. Since *the* early part of this century, there has been scattered evidence that some asteroids might actually be binaries, two bodies orbiting each other at close quarters. But small rocks get putted out Of orbit easily by the perturbing effects of the sun and the other planets, especiall y Jupiter. Dactyl, or biting within a few radii of Ida, is well within its sphere of influence, but it remains to be seen how long it will stay them

The observations

Nearing Jupiter

In July 1994, when still one and a half years from Jupiter, *Galileo* was unexpectedly treated to a grand show: Comet Shoemaker-Levy 9 impacting on the night side of the planet [see "Comet Shoemaker-Levy 9 Meets Jupiter, by David H. Levy, Eugene M. Shoemaker and Carolyn S. Shoemaker; SCIENTIFIC AMERICAN, August]. *Galileo*'s computer sequence had, however, to& specified months before the event, when the times of impact were still very uncer-

1"

tun. To Cover for these uncertainties, many more images had to be recorded than could be returned to the earth over the low-gain antenna. Tape-searching techniques such as those used during the Ida flyby were invoked. Moreover, analysis of the events observed from the earth and the *Hubble Space Telescope* helped astronomers to locate@ play back only the sections of the recording that held data from the impact.

Galileo was able to observe the visible and near-infrared light from the entry itnd explosion of several fragments of the comet. Among the most spectacular images Were those of the last event. Taken in green light at in tervals of 2.33 seconds, these pictures show a gibbous Jupiter with a bright point of light appearing, brightening and then fading away on 'the night side of the planet, marking the fiery death Of the prosaically named W fragment.

Critical data on the large "G" event were also recorded by ultraviolet, photopolarimeter, . radiometer and infrared experiments. They allowed direct calculation of the size, temperature and altitude of the fireball. It emerged as a gJob of about eight kilometers in width and 7,500 kelvins in temperature, rapidly cooling and expanding as it rose in the atmosphere. To analyze ~~all the images~~ will take years.

date

From mid-1994, *Galileo's* dust detector, which measures impacts from micrometeoroids no larger than the particles in cigarette smoke, had begun to record dust streams coming from the direction of Jupiter. This past August, while still 39 million miles from the planet, *Galileo* plowed through the most intense dust storm ever measured. Every day for four weeks the detector was spattered by up to 20,000 particles traveling at 40 to 200 kilometers pet second. The dust grains, which are too small t o damage the craft, may originate either from the rings of Jupiter or from the volcanoes of its moon Io. They probably are electrically charged grains that were accelerated by Jupiter's magnetic field and flung far out into space.

in October *Galileo's* mission planners experienced one more unexpected jolt. The tape recorder, which had served faithfully for years, did not stop rewinding upon reaching the ~~end~~ of the tape. As of this writing, the team's best guess is that the recorder is broken. The spacecraft still has some solid-state memory, which can be used to store and transmit high-resolution images—~~about~~ half the number the tape recorder would have allowed.

no synch beginning may be however, perhaps as much as many

many. So even if the is not co

Galileo's arrival at Jupiter on December 7, 199s, will mark the start of its primary mission. The data from the probe, an extremely valuable but small data set (It can fit on a floppy disk), will be played back in their entirety. *Galileo* will then concentrate on a multitude of measurements of the giant planet, its four largest moons and its mammoth magnetic field.

By that time, the spacecraft's capabilities Will be significantly enhanced. when *Galileo's* computers *were* originally programmed, data-compression techniques were quite primitive. A completely *new* set of software for the computers on board will allow extensive processing, editing and compression of data on board the spacecraft, increasing the information content in each bit ~~by a factor of 10 or more.~~ numerical 10

In addition, the Deep Space Network will have been modified to pick up the faint signals from the low-gain antenna. The DSN is a group of three tracking complexes: at Goldstone, Calif., Madrid, Spain, and Canberra, Australia. Set 120 degrees in longitude apart, the stations permit any spacecraft to be in view at any time. (Tracking time on DSN is an important bargaining chip for NASA in collaborative space projects.)

The antennae are typically used separately to track different spacecraft. But when great sensitivity is required, they can be tuned electronically to create effectively a much larger receiving dish. *Voyager* treed this capability when viewing Uranus and Neptune, and *Galileo* will make routine use of the technique while surveying Jupiter.

These improvements, combined with other changes in the way the spacecraft encodes data, will increase the information capacity of the telecommunications link up to 1,000 bits per second. With this capability the primary goals of *Galileo*—those involving high-resolution data on the objects it will near rind a survey of the magnetic field—will be realized. *Galileo* will view the Jovian satellites with the resolution that *LANDSAT*, for example, images the earth. Some other projects, such as observing Io at close range, measuring magnetospheric phenomena at very high time resolutions, or making a motion picture of, say, the ~~Great Red Spot~~, will not be possible without the high-gain antenna and the tape recorder.

One can never say what might have been discovered by the broad, sweeping look at the Jovian system that was originally envisaged. But the Galileo team has already demonstrated that it can make remarkable discoveries by clever use of extremely low bit rates. I estimate that at least 50 percent of the mission's objectives will be met, and I eagerly anticipate some fascinating surprises. From these new data will flow the understanding and questions to fire the imaginations of the next generation of explorers.

which also set and will monitor the volcanos on Io at resolution 10 times better than HST.

even if the tape recorder cannot be used at all permanently disabled

JUPITER ATMOSPHERIC PROBE will penetrate the planet art December 7, 1995. Much of the heat shield (*below*) will burn away; the rest will fall off after a parachute slows the probe down, exposing its instruments. These devices win measure wind speed, cloud cor" position, lightning frequency and other aspects of the atmosphere.

The Author

TORRENCE V. JOHNSON chairs the group of *Galileo* science investigators. After obtaining his doctorate in planetary science at the California Institute of Technology, he work ~~the National Aeronautics and Space Administration's~~ Planetary Astronomy Laboratory ~~and the National Research Council~~. *Currently* he is a senior research scientist at the Jet Propulsion Laboratory in Pasadena, Calif., where he has assisted with many interplanetary projects, including the Voyager missions.

Further Reading

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JUPITER: THE GIANT PLANET. Reta Beebe. Simon & Schuster, 1994.

ONLINE FROM JUPITER available on the World Wide Web at http://quest.arc.nasa.gov/jupiter.html or via gopher at quest.arc.nasa.gov in Interactive Projects directory.

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